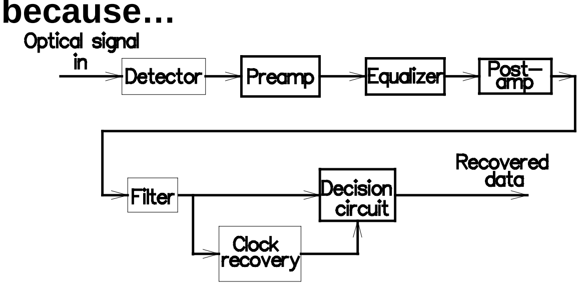
Optical Receivers

- ***Optical receiver components***
  - ***Optical detector*: convert modulated light into electronic signal**
  - ***Preamp*: amplify weak electrical signal**
  - ***Equalizer*: recover bandwidth lost in preamp**
  - ***Postamplifier*: further amplifies signal**
  - ***Filter*: remove unwanted frequency components**
  - ***Clock recovery*: recover clock sent on optical signal**
  - ***Decision circuit*: sample signal and recover data**
- **Receiver design is complicated because…**
  - **Weak optical signal**
  - **Electronic noise present**



- **Clock recovery**
  - ☞ **Low-data-rate receivers**
    - ✳ **Detection done asynchronously**
      - ❖ **Receiver clock not tied to transmitter clock**
    - ✳ **Comparator decides whether pulse present or not**
    - ✳ **Pulses need sharp rise and fall times**
  - ☞ **High-data-rate links**
    - ✳ **Data clock encoded in signal and recovered at receiver**
    - ✳ **Optimum sampling time in bit interval**

Noise

- Noise
  - Produces errors in data
  - Introduced by
    - » Transmitter
    - » Channel
      - Fiber: zero channel noise
    - » Detector
    - » Electronic processing
  - Optical-detector noise different than radio and electronic detectors
    - » Signal-dependent

Receivers: Preview

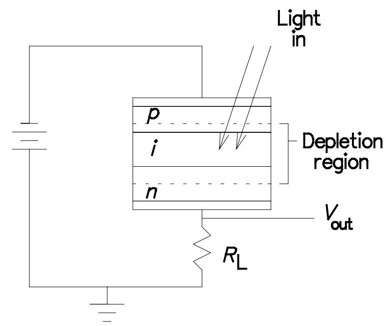
- Detectors
  - Physical operating principles
    - » Pin photodiode
    - » Avalanche photodiode (APD)
  - Operating parameters
  - Noise performance
  - Operating speed.
- Digital receiver design in terms of...
  - Amplifier noise
  - Optimization of signal-to-noise ratio
  - Requirements for equalization amplifier
- Sensitivity of optical receiver is function of...
  - Detector noise and...
  - Preamplifier choice

Receivers: Detector

- **Converts optical input power to current output**
- **Photodetector properties**
  - **Efficiency**
  - **Noise**
  - **Spectral response**
  - **Speed**
  - **Linearity**
  - **IC-compatibility**
  - **Reliability**
  - **Price**
- **Semiconductor photodiodes**
  - ***pin* photodiode**
  - **Avalanche photodiode (APD)**

Photodiodes: Physical Principles

- **Reverse-biased *pin* junction**



- ***Depletion region*** **(no free carriers) around junction**
- **Portion of light absorbed *in depletion region* and...**
  - **Hole-electron pair created**
- **Pair separated and swept out by electric field**
- **Sensed by outside circuitry**
- **Number of hole-electron pairs per second freed**
  - **Linearly dependent on optical power**
  - **Electric current proportional to optical power**

Photodiodes: Spectral Response

- ***Bandgap energy***: energy required to free hole-electron pair

Material	E_g (eV)	λ_{max} (μm)
Si	1.14	1.09
Ge	0.67	1.85
GaAs	1.43	0.867
$In_{0.14}Ga_{0.86}As$	1.15	1.08
$In_{0.53}Ga_{0.47}As$	0.75	1.65

- **Long-λ response: no sensitivity at long λ**
  - **Photon energy**: $hc/\lambda \geq E_g$
  - ***Long wavelength cutoff***

$$\lambda_{\text{max}} = hc/E_g; \quad \Rightarrow \quad \lambda'_{\text{max}}[\mu\text{m}] = 1.24 / E'_g[\text{eV}]$$

  - » **Si: λ_{max} = 1.09 μm, short-λ detector**
  - » **InGaAs & Ge: long-λ (1300, 1550 nm) detectors**

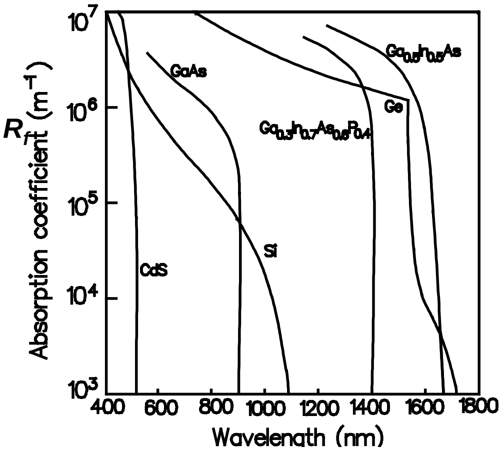
Photodiodes: Spectral Response (cont.)

- Short-λ response
  - No sensitivity at short λ
    - » Light penetration into depletion region...
      - Power absorbed in depletion region...

$$P(w) = P_i e^{-\alpha d}\left(1 - e^{-\alpha w}\right)\left(1 - R_f\right)$$

- – Absorption coefficient: α
- – Depletion region depth: *w*
- – Region begins at depth: *d*
- – Power reflectivity at detector surface: R_f

- Increase *w* with *i* layer of *pin*
- At short wavelengths
  - – α rises dramatically
  - – Strong surface absorption
  - – Little power penetrates

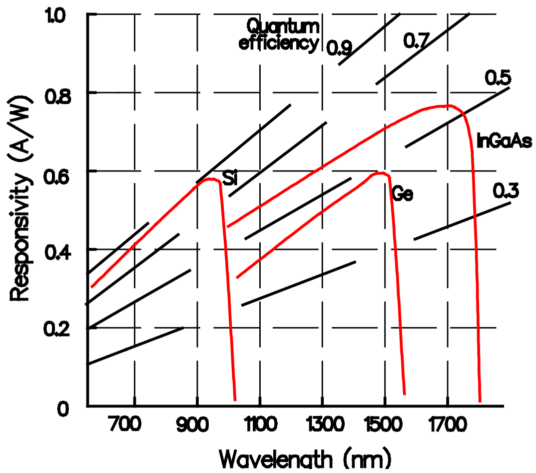


Detectors: Sensitivity

- **Given by responsivity or quantum efficiency:**
  - ***Responsivity:*** **output current per watt of optical power in**
  - ***Quantum efficiency:*** **number of hole-electron pairs generated per photon**

$$\Re = I_{\text{out}} / P_{\text{in}} \qquad \eta = Ihc / qP_i \lambda = hc\Re / q\lambda$$

- **Spectral response...**



- **Ex., detector producing 80 µA for 500 µW input at 850 nm has $\Re$ = 160 mA/W and η = 23.4%**

Detectors: Sensitivity - Probability Approach

asic noise source: quantized nature of light

eak incident signal, output current <u>not</u> exact replica of ideal urrent

– Random generation of charge-carrier pairs by photons

» ***Poisson random process***

- Total carriers generated in time from *t* to *t+T* is random variable
- Average number of carriers

$$\overline{N} = (\eta\lambda/hc)\int_t^{t+T} p(t)\,dt = (\eta\lambda/hc)E$$

– ***E:*** total ***energy*** in interval ***T***

» Probability that number of charges created, ***N***, equals specific number, ***n***,

$$P(N = n) = \overline{N}^{\,n} e^{-\eta\lambda E/hc} / n!$$

$$\rho(t)\,dt = \frac{\Re p(t)}{q}\,dt = \frac{\eta\lambda}{hc}\,p(t)\,dt$$

Detectors: Probability Approach (cont.)

- **Application of Poisson results**
  - **Want probability < 10^{-9} that "0" detected (N = 0) when "1" transmitted; what E is needed?**

$$P(N = n = 0) = \overline{N}^{\,n} e^{-\eta\lambda E/hc} \big/ n! \le 10^{-9}$$

$$P(N = 0) = \overline{N}^{\,0} e^{-\eta\lambda E/hc} \big/ 0! = 1e^{-\eta\lambda E/hc}\ /\ 1 \le 10^{-9}$$

$$E \ge 21hc/q\lambda \quad \text{(i.e., 21 photons)}$$

  - **Require reception of 21 or more photons during bit period when a "1" is transmitted to ensure detection with error probability <10^{-9}**
- **If number of "1"s and "0"s equal and bit period is T_B,**

$$P_{\text{average}} \ge \frac{21hc}{2\eta\lambda T_B} = \frac{21hcB_R}{2\eta\lambda} \qquad (\text{for } P_e \le 10^{-9})$$

Generalization of BER Results

- **For any desired BER (*bit error rate*), need…**

$$e^{\left(-\frac{\eta\lambda E}{hc}\right)} \leq \mathrm{BER} \qquad \text{or} \qquad E \geq \frac{hc}{\eta\lambda}\ln\left(\frac{1}{\mathrm{BER}}\right)$$

- **Minimum required average *power* is...**

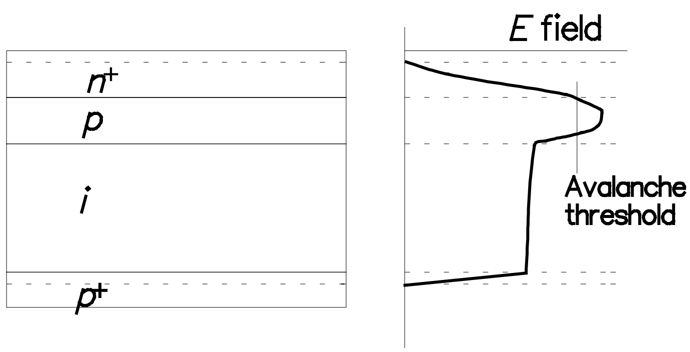
$$P_{\text{average}} = E_{\min}/2T_B = E_{\min}B_R/2$$

- **Theoretical power required to achieve desired BER when limited by light quantization**

Avalanche Photodiode: Physical Principles

- Differences from *pin* diodes
  - Dope *p* and *n* regions higher
  - Narrow *p* region added between *i* and n^+ region (see notes below)
    - » Electric field in this region larger than in depletion region
      - Field accelerates carriers to high velocities
      - Collisions create more hole-electron pairs (*impact ionization*)
- Operating physics
  - Light enters through p^+ region and (ideally) absorbed in *i* region
  - Generated carriers separate and drift across *i* region
  - When electrons enter *p* region, accelerated and impact other atoms, creating more carriers
  - Carriers are accelerated and, in turn, create more carriers (*avalanche effect*)

•Structure



•Ionization by collisions

☞ Field strengths in excess of 3×10^5 V/cm required

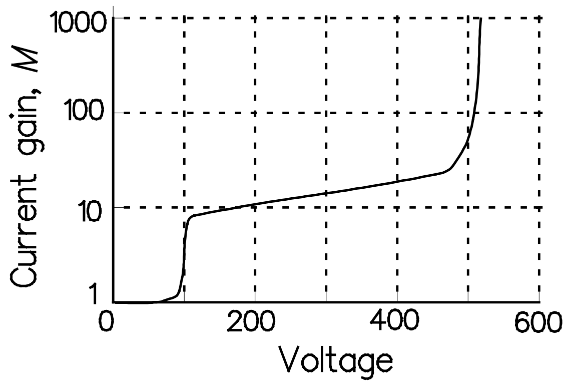
Avalanche Photodiode: Physical Principles(cont.)

- Avalanche multiplies photocurrent
  - *Multiplication factor:* $M = I_M / I$

    I: output current <u>without multiplication</u>
  - Instantaneous multiplication is random value; *M* is *average* multiplication
  - Controlled by reverse bias
    - » *M=1* expensive pin diode
- APD responsivity

$$\Re_{\mathrm{APD}} = \eta q \lambda M / hc = M \Re_0$$

$\Re_0$: responsivity at $M = 1$



Avalanche Photodiode: Ionization Rates and Noise

- Ionization rates
  - ***Hole (electron) ionization rate***: efficiency of creating new hole-electron pair by colliding hole (electron)
- Creation of new hole-electron pair adds noise
  - Minimize noise by maximizing difference in ionization rates
    - » Want only *one* type of carrier responsible for avalanche process
      - Silicon: electron ionization rate is 100× hole ionization rate
      - Ge, GaAs and InGaAs: closer ratios (5x→10x) ⇒ more noise
      - Silicon detectors (short-λ) have less noise than non-silicon (long-λ) detectors

Detectors: Signal-to-Noise Ratio

- Use *power signal-to-noise ratio*
  - *"Signal"* is signal *power* delivered to resistor by signal current
  - *"Noise"* is noise *power* delivered to same resistor
- *Signal-to-noise ratio*, SNR

$$\frac{S}{N} = \frac{P_{\text{signal}}}{P_{\text{noise}}} = \frac{\langle i_s^2 \rangle R}{\langle i_N^2 \rangle R} = \frac{\langle i_s^2 \rangle}{\langle i_N^2 \rangle}$$

  - SNR independent of R; need only mean-square signal and noise currents
- Two noise mechanisms with photodiodes...
  - Shot noise and...
  - Thermal noise

- Signal-to-noise ratio
  - ☞ Arbitrary resistor cancels out of numerator and denominator
    - ✳ SNR independent of resistor
  - ☞ Need to calculate only mean-square signal and noise currents

Detectors: Shot Noise

- Associated with quantization of charge or light
- Mean-square noise current:

$$\langle i_N^2 \rangle_{\text{shot noise}} = 2qIB \qquad (I = I_L + I_{\text{dark}})$$

  - *I*: dc current of device
  - *B:* electronic bandwidth
- *pin* diode dc current:
  - dc output current due to incident light ($I_L = \Re P$)
  - I_{dark}: *dark current*
    - » dc current with no input illumination (e.g., thermal generation and surface leakage currents)
    - » I_{dark} in long-λ detectors ~10x to 100x silicon short-λ detectors
    - » In APDs...
      - *Amplified* bulk dark current, I_{bulk}
      - *Unamplified* surface currents, $I_{surface}$
        - Can be made zero with guard-ring design

- Noise power
  - ☞ This much noise power in frequency region from $f_0-(B/2) \rightarrow f_0+(B/2)$
    - ✳ f_0: center of passband
  - ☞ AC noise power is dependent on *dc current*
  - ☞ $\langle i_N^2 \rangle$ independent of central frequency (f_0) (*white noise*)
- Typical dark current densities

Material	Density (A/cm2)
Silicon	10^{-6}-10^{-7}
InGaAs	10^{-4}-10^{-6}
Ge	10^{-3}

APDs: *Excess* Shot Noise

- Avalanche process contributes more noise described

$$\left\langle i_N^2 \right\rangle_{\text{shot APD}} = 2qI\big|_{M=1} M^2 B F(M)$$

- –*F(M)*: ***excess noise factor***
  - » Extra noise added by avalanche process
  - » *Depends on…*
    - Detector material
    - Shape of *E* field
    - Relative ionization rates
  - » Modeled as...

$$F(M) \approx kM + (1-k)\left(1 + \frac{1}{M}\right) \approx M^x$$

Material	*k*	*x*
Silicon	0.02-0.04	0.3-0.5
Germanium	0.7-1.0	1.0
InGaAs	0.3-0.5	0.5-0.8

- Relative ionization rates
  - ☞ *k* : ratio of electron generation rate to hole rate
  - ☞ or inverse since k≤1
- Excess noise has effect in APD applications
  - ☞ Optimum *M* exists that maximizes SNR
- In APDs, two types of dark current
  - – Surface-defect dark current, I_{surf}
    - » Bypasses gain region
    - » Not amplified
    - » Frequently neglected
    - » Made 0 if reverse-biased guard ring incorporated into diode design
  - – Bulk dark current, I_D
    - » Passes through amplification region and is amplified

Detectors: Thermal Noise

- Any resistive load (or device with associated resistance) produces noise
- Mean-square thermal noise current...

$$\left\langle i_N^2 \right\rangle_{\text{thermal}} = \frac{4kTB}{R}$$

T: noise temperature

B: electronic bandwidth

R: resistance value

– Assumes power delivered to matched load ($R_L = R$)

Detectors: Signal-to-Noise Analysis

- SNR of detector loaded by resistor R_L

$$\frac{S}{N} = \frac{\left.\left\langle i_s^2 \right\rangle\right|_{M=1} M^2}{2q\left(\left. I_L \right|_{M=1} + I_D\right) M^2 F(M) B + 2qI_{\text{surf}} B + \left(4kTB/R_L\right)}$$

  - Numerator: mean-square signal current
  - Denominator
    - » (Amplified) shot noise due to
      - dc signal current (I_L) (*before* amplification)
      - Bulk dark current (I_D)
    - » Shot noise due to surface-leakage dark current I_{surf}
    - » Thermal noise due to load resistor

SNR of pin Diode

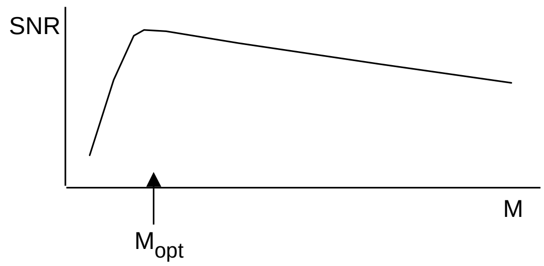
- **For pin photodiode**
  - ***M* = *F(M)* = 1**
  - **Dominant noise source usually thermal noise**
  - **Constant input pulse...**

$$i_s = \eta q \lambda P / hc = \Re P \qquad \left\langle i_s^2 \right\rangle = \Re^2 P^2$$

$$\mathrm{SNR}_{\text{pin diode}} \approx \frac{\Re^2 P^2}{4kTB / R_L}$$

SNR of APDs

- For small *M*: thermal noise dominant; SNR increases with *M*
- Large *M: $M^2F(M)$* makes shot noise dominant; SNR decreases with *M*



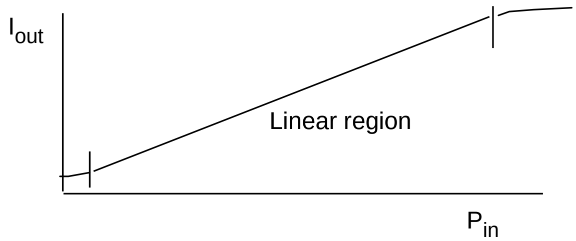
  - SNR has a maximum SNR at optimum *M*
- Optimum *M:*

$$M_{\mathrm{opt}} = \left(\frac{2qI_{\mathrm{surf}} + (4kT/R_L)}{xq(I_L + I_D)} \right)^{\frac{1}{2+x}}$$

- Si APDs: $M_{opt} = 80 \rightarrow 100$
  - SNR improves $40x \rightarrow 50x$ ($16 \rightarrow 17$ dB)
  - Excessive noise in long-λ APDs restricts use

Detectors: Linearity

- ***Linearity***: of output current vs. optical input power curve



- **Required for analog signal fidelity**
- **PIN diodes:**
  - **Excellent**
  - **Typically linear over 6 decades of input**
- **APDs:**
  - **Not quite as good**
  - **High linearity usually not required for weak signals**

PIN Diode: Speed of Response

- **Factors**
  1. ***Transit time***
     - » **Time to *drift* across depletion region: $\tau = w/\langle v\rangle$**
       - **$\langle v\rangle$:Scattering-limited velocity** (Si: 1.0×10^5 m/s)
       - **Depletion width of 10 μm; response time $\approx$ 0.1 ns** (~10 GHz bandwidth)
       - **Minimize by making *w* small** (decreases sensitivity)
  2. ***Diffusion time***
     - » **Time for carriers created in *p* or *n* material** (close to depletion region boundary) **to diffuse into depletion region**
       - **Diffusion process is *slow***
       - **Small fraction of carriers involved**
     - » **Minimize by ensuring that most of carriers generated in depletion region**
       - **Make *w* large** ($w \gg 1/\alpha$)
         - [Increased depletion region increases transit time, however]

PIN Diode: Speed of Response (cont.)

3. ***RC*** **time constant of device and associated circuitry**

- **Bandwidth limitation:** $B_{max} = 1/2\pi RC_d$
  - » ***R*****: input resistance of preamplifier in parallel with load and device resistance** (keep small for fast receiver, R~50 Ω)
  - » ***C_d device capacitance:*** $= \varepsilon A/w$
    - **Reduce C_d by making A small** (decreased sensitivity) **and *w* large** (increases transit time, causing tradeoff)
      - **Usual compromise:** $w \approx 2/\alpha$
    - **Typical C_d < 1 pF**

- **Primary limit in well-designed, fast pin diode** (used in low-resistance circuit) **: transit time across depletion region**
- **Fast silicon devices have response <1 ns** (multi-GHz bandwidths)

APD: Speed of Response

- Response typically slower than fast *pin* diodes
  - Carriers must drift into avalanche region
  - Created carriers must drift back,
    - » Makes total transit time ~2x longer

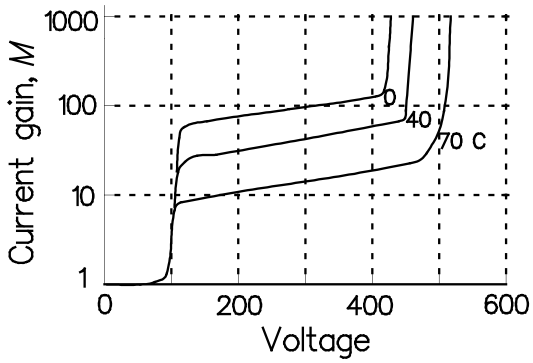
- Constant gain-bandwidth product constraint
  - Caused by giving avalanche process time to occur
  - Typical value: $M \cdot BW \leq 200$ GHz

Detectors: Reliability

- No major problem
- Based on accelerated-temperature lifetime testing
  - Projected lifetime: ~10^8 hours

APDs: Temperature Sensitivity

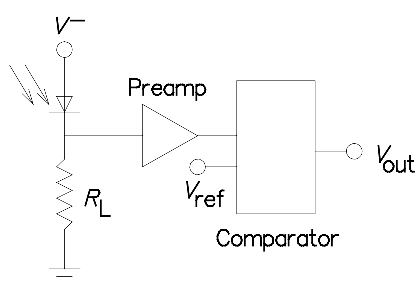
- *M* quite temperature sensitive

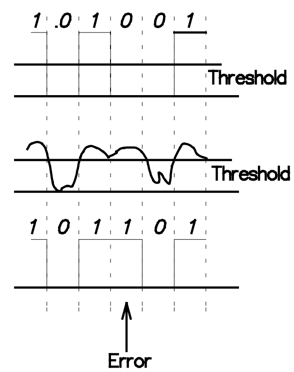


- Use temperature-compensating feedback circuit to minimize effect

Detector Power and Bit-Error-Rate Revisited

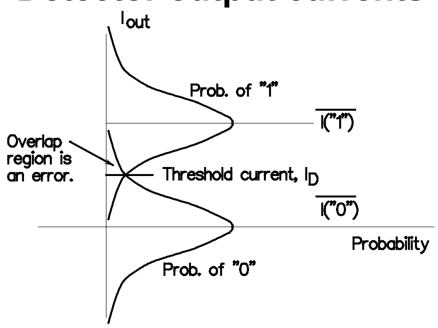
- **Digital receiver** **(left)**
  - **Detects optical signal and converts to electrical signal**
  - **Decides whether electrical output represents "1" or "0"** **(using decision circuit), and...**
  - **Generates logic voltage output**
- **Threshold voltage** **(decision level)** **critical to determining bit error rate (BER)**
  - **Threshold expressed as fraction *k* of expected output of "1"**
  - **Errors made due to noise (right)**





Receivers: Noise Models

- Simplified noise assumptions...
  - Detector output currents are Gaussian random variables



$$p(i_N)\, di_N = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(i_N - \bar{i})^2}{2\sigma^2}} di_N$$

  - Mean value of current for logical "1": $\overline{i(1)}$
  - Mean value of output current for logical "0": $\overline{i(0)}$ (= 0, later)
  - Standard deviation σ is measure of width...
    - » Mean square noise current: $\langle i_N^2 \rangle = \sigma^2$
    - » Assume standard deviations σ_1 and σ_0 are equal

Receivers: Noise Models (cont.)

- **Errors**
  - **"0" sent: error if i_N positive and $i_N > k\overline{i_N(1)}$**
  - **"1" sent: error if i_N negative and $i_N > (1-k)\overline{i_N(1)}$**

  - **Total probability of error is…**

$$P_e = P(\mathbf{0}|\mathbf{1})\,P(\mathbf{1}) + P(\mathbf{1}|\mathbf{0})\,P(\mathbf{0})$$

  - **If P(1) = 1/2 and P(0) = 1/2**
    - » **Combined error probability is...**

$$P_e = (1/2)\,P\left[i_N < -(1-k)\overline{i(\mathbf{1})}\right] + (1/2)\,P\left[i_N > k\overline{i(\mathbf{1})}\right]$$

Detectors: Threshold Location and BER

- **Substituting Gaussian distribution, can show that probability of error is...**

$$P_e = \mathrm{BER} = \frac{1}{4}\left[\mathrm{erfc}\left(\frac{\bar{i}(1) - I_D}{\sigma_1\sqrt{2}}\right) + \mathrm{erfc}\left(\frac{I_D - \bar{i}(0)}{\sigma_0\sqrt{2}}\right) + \right] \qquad \left(I_D \equiv k\,\bar{i}(1)\right)$$

- **Optimum threshold location to minimize BER is…**

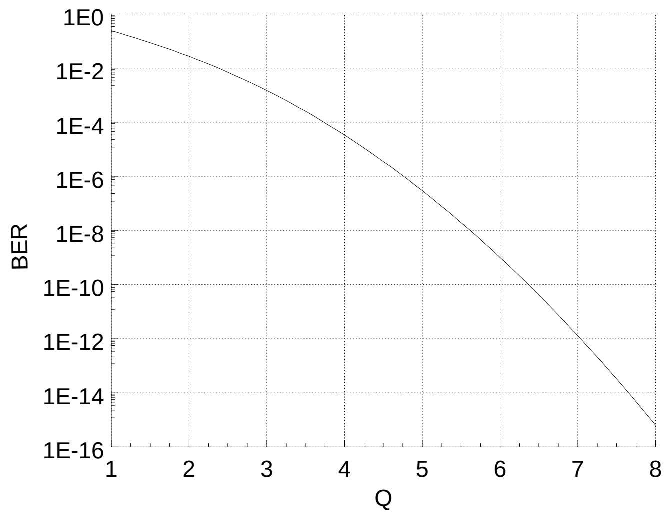
$$\frac{\bar{i}(1) - I_D}{\sigma_1\sqrt{2}} = \frac{I_D - \bar{i}(0)}{\sigma_0\sqrt{2}} = \mathrm{Q} \quad \Rightarrow \quad I_D = \frac{\sigma_0\bar{i}(1) + \sigma_0\bar{i}(0)}{\sigma_0 + \sigma_1}$$

- **BER is...**

$$\mathrm{BER} = \frac{1}{2}\mathrm{erfc}\left(\frac{Q}{2}\right) \approx \frac{e^{-\frac{Q^2}{2}}}{Q\sqrt{2\pi}} \quad (\text{for } Q > 3)$$

BER vs. *Q*

Fig. 6.12
p. 186



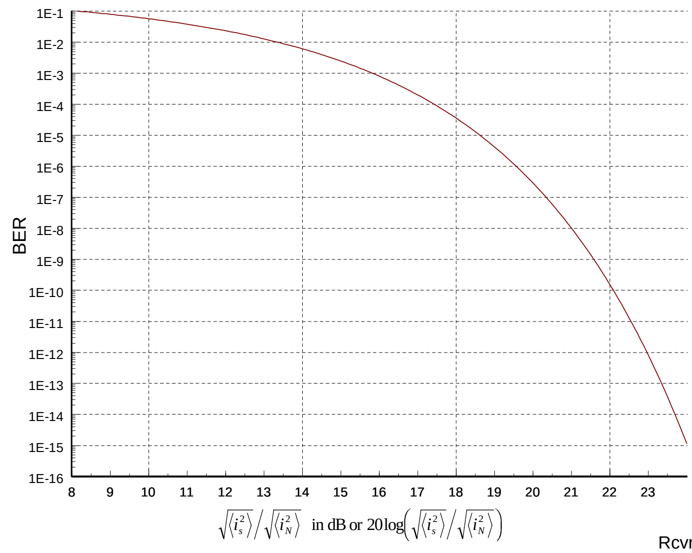
- **Benchmarks:**
  - **Q= 4.76 (BER =10^{-6})**
  - **Q = 6.00 (BER =10^{-9})**
  - **Q= 7.04 (BER =10^{-12})**

BER vs. SNR

- **Assume**
  - $\sigma_0 = \sigma_1 = \sigma = \sqrt{\langle i_N^2 \rangle}$
  - $I_D = [\overline{i(1)}+\overline{i(0)}]/2$ **(i.e., midway)**
  - **then...**

Fig. 6.13
p. 187

$$\mathrm{BER} = \frac{1}{2}\mathrm{erfc}\left(\frac{\sqrt{\mathrm{SNR}}}{2\sqrt{2}}\right)$$



Receivers: Minimum Required Power (cont.)

- Sample example (pp. 187–188, but BER = 10^{-9})
- Begin with desired BER; find required SNR...
  - » BER = 10^{-9} needs $\sqrt{\langle i_s^2 \rangle} \big/ \sqrt{< i_N^2 >} = 21.5 \text{ dB} \Rightarrow 11.89$

  Limiting noise (e.g., thermal noise for pin diode or shot noise for APD), and calculate...

$$\sqrt{< i_N^2 >} = \sqrt{\frac{4kTB}{R_L}} = \sqrt{\frac{(4)(1.38 \times 10^{-23})(400)(10^7)}{50}} = 6.65 \times 10^{-8}$$

  – From required SNR, find $\sqrt{\langle i_s^2 \rangle}$...

$$\sqrt{\langle i_s^2 \rangle} = \sqrt{\text{SNR}_{\text{req}}}\sqrt{< i_N^2 >} = (11.89)(6.65 \times 10^{-8}) = 7.90 \times 10^{-7}\,\text{A}$$

  – Find the optical power required at the detector to achieve specified BER..

$$P_{\min} = \sqrt{< i_s^2 >} \big/ \Re = 7.90 \times 10^{-7} / 0.4 = 1.976 \times 10^{-6} \text{ W} = 1.976\ \mu\text{W}$$

- Ex.,
  - ☞ BER of 10^{-6} with photodiode detector
  - ☞ Responsivity of 0.4 A/W
  - ☞ SNR limited by thermal noise (with a 50 Ω load, a 400K noise temperature, and a 10 MHz noise bandwidth)
  - ☞ Requires $<i_s>/<i_N> = 10^{19.6/20} = 9.55$ and $P_{min} = 1.587\ \mu$W
- Have neglected pulses that spread out of bit periods
  - ☞ Effect can lead to form of noise called *intersymbol interference*
  - ☞ Minimize with
    - ✳ Equalization amplifier or
    - ✳ Make bit spacing T_b > 4 times RMS pulse spreading of fiber

Receivers: Noise and Sensitivity

- ***Receiver front-end:***
  - Combination of detector and preamplifier
- **Receiver noise properties set by...**
  - » **Detector**
  - » **Amplifier**
    - **Not detector alone**
- **Generally three common receiver implementations**
  1. ***Low-impedance front-end***
  2. ***Integrating front-end***
  3. ***Transimpedance amplifier front-end***
  - **(Some do *not* fall into these categories)**

Receivers: 1. Low-impedance Front-End

- Detector operates into low-impedance amplifier
  - Usually 50 Ω impedance
  - Ready availability of wideband RF amplifiers
- Choose R_L equal to amplifier input resistance
  - e.g., 50 Ω amplifier calls for 50 Ω load
- Poor preamplifier (not recommended)
  - Low sensitivity...
    - Small voltage across amplifier & load resistance
    - High thermal noise from small load/amplifier resistance

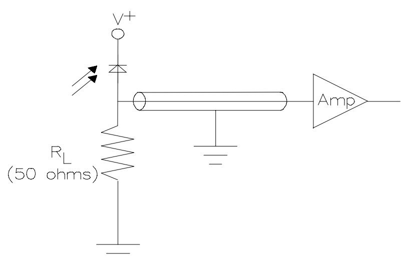
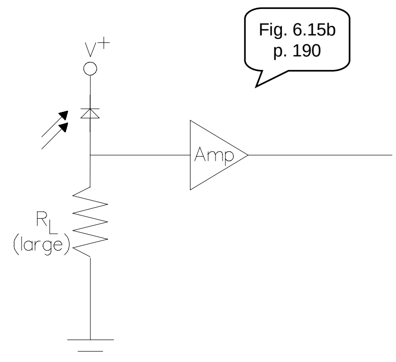


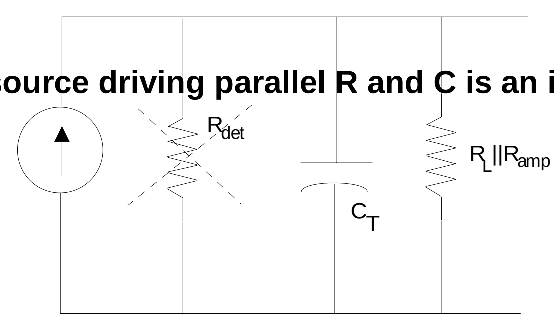
Fig. 6.15a
p. 190

Receivers: 2. High-impedance Front-End

- Amplifier has high R_{in}
  - $R_L = R_{in}$
- Larger signal voltage and less thermal noise
  - Amplifier can use FET input for large R_{in}
- Capacitances in parallel with load/amplifier resistance:
  - Total: C_T
    - » Detector capacitance plus
    - » Amplifier input capacitance plus
    - » Parasitic capacitances
- Current generator driving parallel *RC* circuit
  - Integrator ***(integrating front-end)***



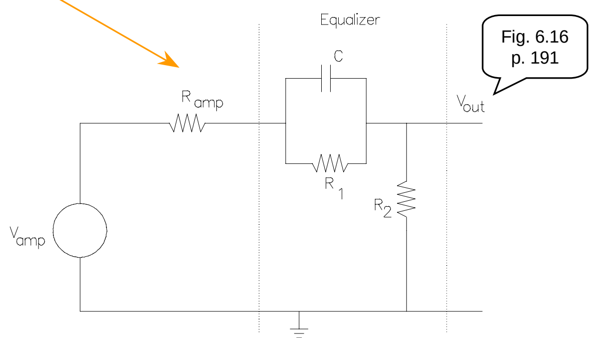
- **Equivalent circuit of receiver**
  - ☞ $R_{det} >> R_L||R_{amp}$
  - ☞ **Current source driving parallel R and C is an integrator**



Receivers: 2. High-impedance Front-End (cont.)

- Bandwidth: $1/2\pi R_{parallel} C_T$
  - » $R_{parallel}$: 100s kΩ $\rightarrow$ few MΩ
  - » C_T: few pF or less
  - » Bandwidth $\leq$ kHz range
    - Too low for high bit-rate
- *Equalization amplifier* compensates for low bandwidth (see example)
  - – Choose R_1 & C $\Rightarrow 1/R_1C = 1/R_LC_T$
    - » Equalizer zero cancels front-end pole
    - » Combined bandwidth > front-end bandwidth

- Pro: best sensitivity of all configurations
- Con:
  - – Requires additional circuit
  - – Limits dynamic range
  - – Limits dc response
    - » Integrated low-frequency components saturate preamp



- Preamp/detector
  - ☞ Equivalent voltage source $V_{amp}(\omega)$ and resistance R_{amp}
  - ☞ Transfer function of circuit is
  - ☞ Combined bandwidth

✳Making $R_1 >> R_{amp} + R_2$ ensures higher bandwidth than integrating front-end alone

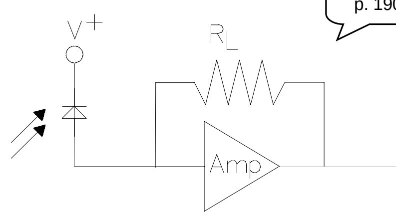
$$\frac{V_{out}}{V_{amp}} = \frac{R_2(1 + j\omega R_1 C)}{R_1 + R_{amp} + R_2 + j\omega R_1 C(R_{amp} + R_2)}$$

$$f_{\text{combined}} = \frac{1}{R_1 C} \frac{R_1 + R_{amp} + R_2}{R_{amp} + R_2}$$

Receivers: 3. Transimpedance Front-End

- **Current-to-voltage convertor (gain of R_L)**
  - **Bandwidth: A (amplifier gain)$/2\pi R_L C_T$**
  - **No equalization amp**
- **Low-frequency components reduced by $1/(A+1)$**
  - **Reduces amplifier saturation**
  - **Increases dynamic range**
- **Pros:**
  - **Simple (no equalization amp)**
  - **Good bandwidth**
  - **Good dynamic range**
- **Cons:**
  - **More noise (less sensitivity) than integrating front-end**

Fig. 6.15c p. 190



•Bandwidth

☞ **Factor of $A+1$ larger than unequalized integrating front-end)**

Receivers: Amplifier Noise Effects

- **Actual receivers: amplifier noise dominates detector noise**
- **How to account for amplifier noise?**

  1. Low-impedance front-ends

  – **Amplifier *noise figure* F_n**

  » **Describes noise added by amplifier**

  » **Usually specified in dB; convert to numerical value for formulas**

  » **Good low-noise amplifier: F_n < 3 dB;** otherwise, ≥ 6 dB

  – **SNR:**

$$\frac{S}{N}=\frac{G^2\Re P M^2}{2q\left(\Re P+I_{\text{dark}}\right)G^2M^2F(M)B+\left(4kTBF_n\,G^2/R_L\right)}$$

Additional noise due to amplifier

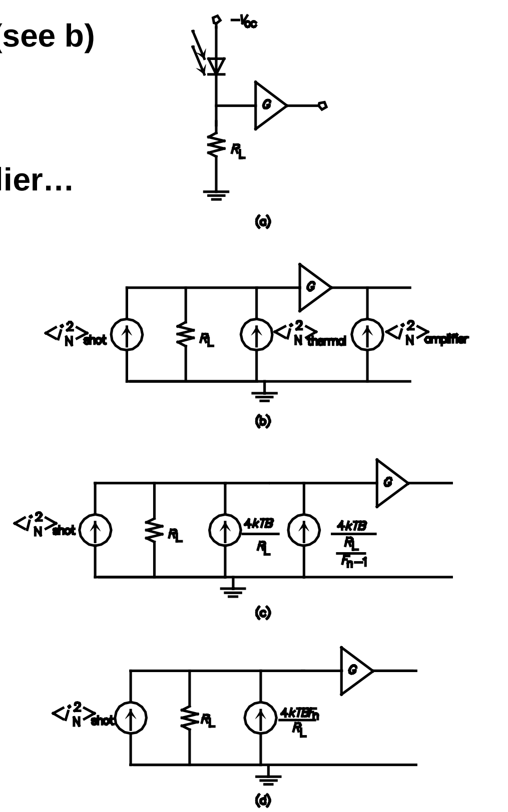
  » ***pin* diode: $M = F(M) = 1$**

  » **APD: SNR maximum at M_{opt}**

$$M_{\text{opt}}=\left(\frac{2qI_{\text{surf}}+\left(4kTF_n/R_L\right)}{xq\left(\Re P+I_{\text{dark}}\right)}\right)^{\frac{1}{2+x}}$$

- **See text for more detail on noise figure...**
  - ☞ **Amplifier generates thermal noise at out put (see b)**
  - ☞ **Amplifier noise is "referred" back to input**
    - ✳**As if noise was generated by R_L (see c)**
    - ✳**F_N is value that gives correct noise multiplier…**

$$F_N=1+\frac{\left\langle i_N^2\right\rangle_{\text{amplifier}}R_L}{4kTBG^2}$$



Note: All current generator labels show mean-square currents

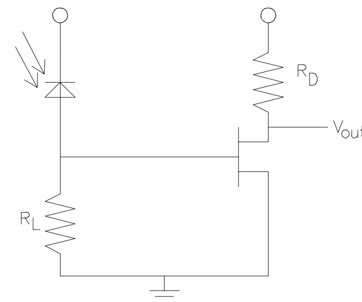
    - ✳**Equivalent resistance of RL/FN generates**
    - ✳ **same amount of noise (see d)**

Receivers: FET Front-Ends

2. FET front-ends

- **Can use either FETs or bipolar junction transistors**
  - **FETs: superior noise properties**
  - **GaAs microwave FETs for high-data-rate**

Fig. 6.18
p. 195



- **Representative common-source preamp**
  - **Principal sources of noise**
    - » **Thermal noise from**
      - **FET channel resistance**
      - **Load resistor R_L**
    - » **Shot noise due to FET gate leakage current**
    - » **Electronic *1/f* noise of FET**
    - » **See next page**

Receivers: FET Front-Ends (cont.)

- **Mean-square noise current of amplifier**

Eq. 6.102 p. 194

$$\langle i_N^2 \rangle_{\text{amp}} = (4kT/R_L) I_2 B_R + 2qI_{\text{gate}} I_2 B_R + (4kT\Gamma/g_m)(2\pi C_T^2) f_c I_f B_R^2 + (4kT\Gamma/g_m)(2\pi C_T^2) I_3 B_R^3$$

- B_R: bit rate
- R_L: load or feedback resistor
- I_{gate}: FET gate leakage current
- g_m: FET transconductance
- C_T: total input capacitance
- f_c: FET 1/*f*-noise corner frequency
- Γ: FET channel noise factor
- I_1, I_2, I_3, and I_f : *Personick integrals* (constants depending on input/output pulse shapes)
- Channel-noise factor Γ describes noise contribution from channel resistance and gate-induced noise
- $C_T = C_d + C_s + C_{gs} + C_{gd}$
  - » C_d: detector capacitance
  - » C_s: stray capacitance,
  - » C_{gs}: FET gate-to-source capacitance
  - » C_{gd}: gate-to-drain capacitance
- Corner frequency f_c of 1/*f* noise
  - » FET parameter
  - » Frequency where device 1/*f* electronic noise equals thermal noise of channel (characterized by Γ)
- Typical values shown in text and notes

Rcvrs-42

- **Personick integrals**
  - ☞ **Values shown below**
  - ☞ **Depend on pulse shape entering and leaving fiber** **(rectangular input and raised cosine out)**
  - ☞ **Type of coding**
    - ✳**NRZ (non-return-to-zero) coding**
      - ❖**Usual on-off coding that follows data**
    - ✳**RZ (return-to-zero) coding**
      - ❖**Data transition every bit period**
      - ❖**Used to encode clock on data**
- **Stray capacitance, C_s**
  - ☞ **Usually estimated o** **from measured data**
  - ☞ **Minimize by using I** **preamp combinations)**

Table 6.5 p. 196

	Coding NRZ	RZ
I_1	0.548	0.500
I_2	0.562	0.403
I_3	0.0868	0.0361
I_f	0.184	0.0984

Table 6.4 p. 195

Parameter	GaAs MESFET	Si MOSFET	Si JFET
g_m (mS)	15-50	20-40	5-10
C_{gs} (pF)	0.2-0.5	0.5-1.0	3-6
C_{gd} (pF)	0.01-0.05	0.05-0.1	0.5-1.0
Γ	1.1-1.75	1.5-3.0	0.7
I_{gate} (nA)	1-1,000	0	0.01-0.1
f_c (MHz)	10-100	1-10	<0.1

Receivers: FET Front-End Noise (cont.)

Eq. 6.102
p. 194

$$\langle i_N^2 \rangle_{\text{amp}} = (4kT/R_L) I_2 B_R + 2qI_{\text{gate}} I_2 B_R + (4kT\Gamma/g_m)(2\pi C_T^2) f_c I_f B_R^2 + (4kT\Gamma/g_m)(2\pi C_T^2) I_3 B_R^3$$

- **First term**
  - **Thermal noise of load resistor**
  - **Make resistor large...**
    - **But reduces receiver dynamic range**
- **Second term**
  - **Shot noise of gate leakage current**
  - **Choose FET with low value of I_{gate}**
- **Third term**
  - **1/f noise of preamp**
  - **Choose FET with low 1/f noise (low value of f_c)**
- **Fourth term**
  - **FET channel noise**
  - **Choose FET with maximum value of g_m/C_T^2**

Receivers: Noise in FET Front-Ends (cont.)

- **High-bit-rate designs**
  - ***Short-circuit common-source gain-bandwidth product***

$$f_T = \frac{g_m}{2\pi\left(C_{gs} + C_{gd}\right)}$$

    - » **Used to describe FET preamp wideband performance**
  - **Usually interested in optimizing receiver performance at high bit rates...**
    - » **Noise dominated by fourth term (due to B_R^3 dependence) so...**
    - » **Minimum noise current:**

Eq. 6.105
p. 196

$$\left\langle i_N^2 \right\rangle_{\text{amp min}} = \left(32kT\right)\frac{\Gamma\left(C_d + C_s\right)}{f_T} I_3 B_R^3 \quad \left(\text{for large } B_R\right)$$

    - » **Lowest amplifier noise when FET chosen that has maximum figure of merit of...**

$$\text{FOM}_{\text{FET}} = \frac{f_T}{\Gamma\left(C_d + C_s\right)}$$

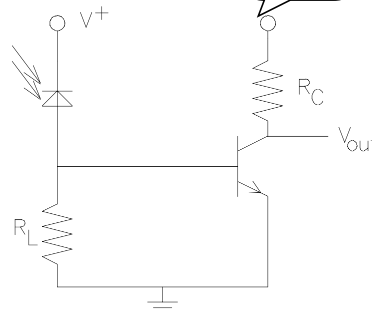
•Note: Choice of best FET depends on capacitance of optical detector

☞ **If you change detector to one with different Cd, also change preamp FET**

Receivers: Noise in BJT Front-Ends

- **Bipolar preamplifiers in some receiver front-ends**
  - **Low bit rates: noise higher than FETs (not recommended)**
  - **High bit rates: comparable noise**
- **Representative common-emitter preamp**

Fig. 6.19
p. 197



- **Principal noise sources:**
  - **Thermal noise from the load resistor R_L**
  - **Shot noise due to base and collector bias currents (I_b and I_C)**
  - **Thermal noise from base-spreading resistance $r_{bb'}$**
- **Amplifier mean-square noise current...**

Eq. 6.107
p. 196

$$\left\langle i_N^2 \right\rangle_{\text{amp}} = \left(4kT/R_L\right) I_2 B + 2qI_b I_2 B + \left(2qI_c/g_m^2\right)\left(2\pi C_T^2\right) I_3 B^3$$
$$+4kTr_{bb'}\left[2\pi\left(C_d + C_s\right)\right]^2 I_3 B^3$$

- **Typical BJT parameters**

Parameter	Value
β	100
$r_{bb'}$	20 Ω
$C_{b'c}$	0.8 pF
f_T	10 GHz

Receivers: Noise in BJT Front-Ends (cont.)

$$\langle i_N^2 \rangle_{\text{amp}} = (4kT/R_L) I_2 B + 2qI_b I_2 B + (2qI_c/g_m^2)(2\pi C_T^2) I_3 B^3 + 4kTr_{bb'}[2\pi(C_d + C_s)]^2 I_3 B^3$$

Eq. 6.107
p. 196

- **Parameters...**
  - **β: transistor current gain**
  - **Transistor transconductance (depends on collector bias):**
    - $g_m = I_c/V_T$ **(with $V_T = kT/q$)**
  - **Total capacitance:**
    - $C_T = C_d + C_s + C_{b'e} + C_{b'c}$
    - **$C_{b'e}$ and $C_{b'c}$: small-signal hybrid-pi model**
      - **Capacitances depend on bias current** (see notes or text)
  - **f_T: "short-circuit common-emitter bandwidth product**

- **There is optimum bias current to minimize noise**

  $I_{c\text{ optimum}} = 2\pi C_0 f_T V_T\, \Psi(B_R)$

  Eq. 6.112
  p. 197

  where $\Psi(B_R) = 1\Big/\sqrt{1 + \left(I_2 f_T^2 / \beta I_3 B_R^2\right)}$ and

  C_0: "total capacitance at zero bias"

  $C_0 = C_d + C_s + C_{b'c} + C_{je}$

- **Mean-square amplifier noise current at optimum bias…**

  See Eq. 6.117 on p. 198 or in notes below

- **Minimize noise by maximizing...**

  Eq. 6.118
  p. 198

$$\text{FOM}_{\text{BJT}} = \frac{2 f_T}{C_0 + \pi f_T r_{bb'}(C_d + C_s)} \quad (\text{for large } B_R)$$

$$\approx \frac{2 f_T}{C_0} \quad (\text{for large } B_R \text{ and small } R_{bb'})$$

- **Base-emitter capacitance $C_{b'e}$ is function of I_c...**
  - ☞ **Two components: $C_{b'e} = C_{je} + I_c/2\pi V_T f_T$**
    - ✳ **C_{je}: current-independent junction capacitance**
    - ✳ **Second term: "diffusion capacitance"**
      - ❖ **f_T : "short-circuit common-emitter gain-bandwidth product"**
  - ☞ **There exists an "optimum collector current" to minimize noise…**

$$I_{c\text{ optimum}} = 2\pi C_0 f_T V_T \Psi(B_R) \quad \text{where } C_0 = C_d + C_s + C_{b'c} + C_{je} \quad \text{and} \quad \Psi(B_R) = 1\Bigg/\sqrt{1 + \frac{I_2 f_T^2}{\beta I_3 B_R^2}}$$

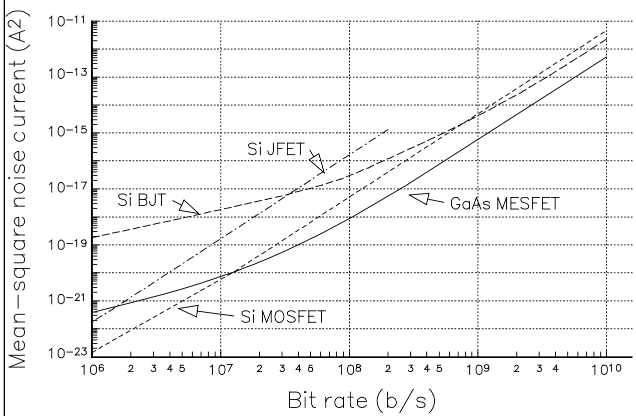
  - ☞ **Mean-square amplifier noise current at optimum bias current**

$$\langle i_N^2 \rangle_{\text{BJT amplifier}}\Big|_{I_C = I_{c\text{ optimum}}} = \frac{4kTI_2 B_R}{R_L} + \frac{4\pi kTC_0 f_T \Psi(B_R) I_2 B_R}{\beta} + \frac{4\pi kTC_0[1 + \Psi(B_R)]^2 I_3 B_R^3}{f_T \Psi(B_R)} + 4kTr_{b'b}[2\pi(C_d + C_s)]^2 I_3 B_R^3$$

  - ☞ **Total capacitance, C_T, can be written in terms of $\Psi(B_R)$ as $C_T = C_0[\,1 + \Psi(B)]$**

Comparison of Noise: FET and BJT Front-Ends

Fig. 6.20
p. 199



- **Low B_R: FET front-end superior to BJT**
- **High B_R: BJT comparable to FET**
- **FET front-ends**
  - **Low B_R: Si MOSFET slightly advantageous**
  - **High B_R:**
    - » **GaAs MESFET slightly superior**
    - » **Si JFETs not suitable**
      - **Relatively low gain-bandwidth product**
        - **Lose gain above ~200 Mb/s**

- **FET & BJT parameters**

- **Detector plus stray capacitance (C_d + C_s) = 0.2 pF; $R_L \approx \infty$**
- **BJT bias current**
  - ☞ **Optimum bias current used if >0.1 mA;**
    - ✳**β starts to fall for bias currents below this value**
  - ☞ **When optimum bias current < 0.1 mA**
    - ✳**I_c = 0.1 mA assumed**

Parameter	Value
β	100
$r_{bb'}$	20 Ω
C_{bc}	0.2 pF
C_{be}	0.8 pF
f_T	10 GHz

	GaAs MESFET	Si MOSFET	Si JFET
g_m (mS)	40	30	6
C_{gs} (pF)	0.38	0.8	4.0
C_{gd} (pF)	0.02	0.1	0.8
Γ	1.1	2.0	0.7
I_{gate} (nA)	2.0	0	0.05
f_c (MHz)	30	1.0	0

Receivers: Sensitivity of Detectors + Front-Ends

- **Power required on receiver**
  - **To achieve BER in presence of *both*...**
    - » **Detector noise *and...***
    - » **Amplifier noise**
- **First will consider pin receiver and, then, more-complicated case of APD receiver**

Receivers: PIN Diode/Preamp Sensitivity

- **>20 dB above quantum limit**
  - **Neglect signal-related shot noise**
- **Total mean-square noise current:** $\left\langle i_N^2 \right\rangle_{\text{Total}} = \left\langle i_N^2 \right\rangle_{\text{amp}} + 2qI_{\text{dark}} I_2 B$
- **Find required SNR for desired BER (from BER vs. SNR equation or curve)**
- **Detector power for pin diode receiver...**

$$P = \left(hc\text{SNR}/\text{q}\lambda\right)\sqrt{\left\langle i_N^2 \right\rangle_{\text{Total}}}$$

- ***P* calculated and plotted as function of *B_R*,**
  - **Once pin diode parameters and...**
  - **Amplifier type and parameters are known**
- **Straight-forward application of SNR concepts**

Receivers: APD/Preamp Sensitivity

- More difficult since...
  - M is additional variable and...
  - Excess noise present
    - » M_{opt} gives best sensitivity (depends on device, preamplifier noise, and B_R)

- ***At $M=M_{opt}$,***
  - APD noise ≈ preamplifier noise
  - Dark-current shot noise: $\langle i_N^2 \rangle_{\text{dark}} \approx 2qI_{\text{surface}} I_2 B_R + 2qI_{\text{D bulk}} M^2 F(M) I_2 B_R$
  - Required power for an APD receiver is…

$$P \approx \left(\frac{hc}{q\lambda}\right) Q \left[QqB_R I_1 F(M) + \sqrt{\frac{\langle i_N^2 \rangle_{\text{Total}}}{M^2} + 2qI_{\text{D}} F(M) B_R I_2} \right]$$

Q: Q-parameter required by BER

I_1 and I_2: Personick integrals

$\langle i_N^2 \rangle_{Total} = \langle i_N^2 \rangle_{amp} + 2qI_{surf} I_2 B$

- *Continue on next slide...*

Receivers: APD/Preamp Sensitivity (cont.)

- If I_D is small enough that it adds negligible noise (true for short-λ detectors)...
  - Required receiver power simplifies to...

$$P = (hcQ/q\lambda)\left(\left(\sqrt{\langle i_N^2 \rangle_{\text{Total}}}\Big/M\right) + qQBI_1F(M)\right)$$

  - Optimum gain

$$M_{\text{opt}} = \left(1\big/\sqrt{k}\right)\sqrt{\left(\sqrt{\langle i_N^2 \rangle_{\text{Total}}}\Big/qI_1BQ\right) - k + 1}$$

- If I_D ***not*** negligible (long-λ detectors)...
  - M_{opt} smaller than value predicted (M_{opt} found graphically or numerically at each B_R by finding M that minimizes receiver power)
  - Calculate total noise and sensitivity as function of B_R

Receivers: Extinction Ratio Effects

- ***Extinction ratio***: $r = P(0)/P(1)$
  - Indicates if source turned off for "1"
- Extinction ratio >1
  - Reduces receiver sensitivity *(sensitivity penalty)*
    - » Shot noise associated with reception of "0"
    - » Not all of received optical power being modulated
  - PIN diode receiver
    - » Power for desired BER is $(1+r)/(1-r)$ *larger*
  - APD receiver
    - » Increases required power in complicated fashion
    - » r affects M_{opt} (found numerically)

Receivers: Eye Pattern Analysis

- Measures speed response and noise

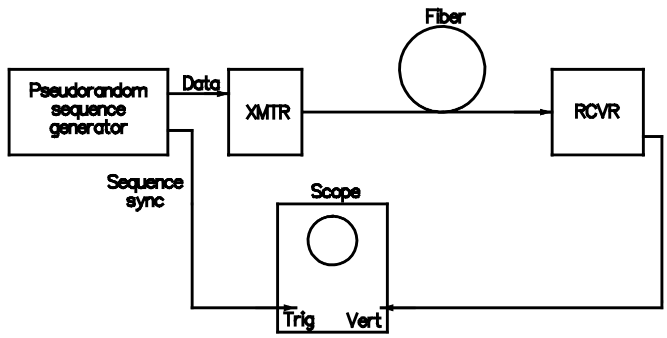


Fig. 6.21 p. 202

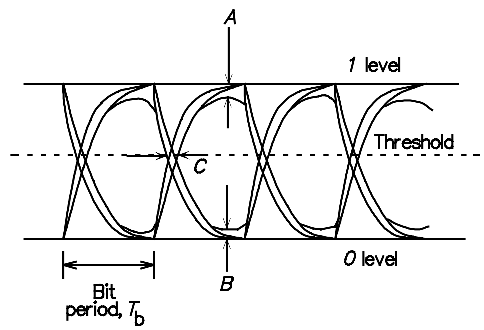


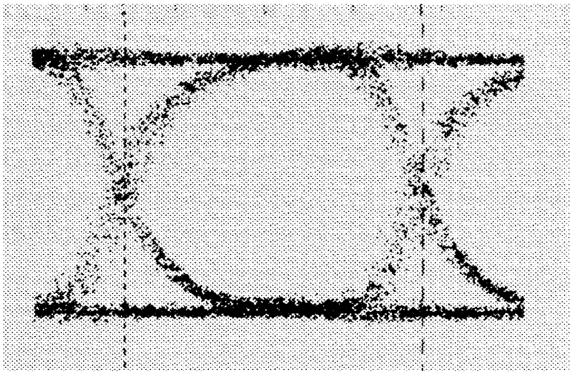
Fig. 6.22 p. 202

- **Digital transmission characteristics**
  - ☞ **Horizontal width: optimum *sampling time interval* for signal to be sampled**
  - ☞ **Vertical height: *Amplitude distortion* of signal**
    - ❖**As f_{max} is reached, vertical height of eye decreases; eye closes**
  - ☞ **Spacing “A": noise when 1 is sent**
  - ☞ **Spacing “B": noise when 0 is sent.**
  - ☞ **Width of `”C": *timing jitter* (or *edge jitter*)**
    - ✳***Jitter* defined as**
  - ☞ **Rise (and fall) times from rise (and fall) times of eye**
    - ✳**Needs long strings of logical 1s and 0s in data stream**

$$J(\%) = \left(\Delta T / T_b\right) \times 100\%$$

Example of Eye Pattern from Sampling ‘Scope

- Experimental performance of high bit-rate link measured from *eye pattern*
- Time-domain measurement



- Pattern is superposition of outputs from pseudorandom stream of data pulses

Receivers: Summary

- Properties of pin diodes and APDs

Tabel 6.8
p. 203

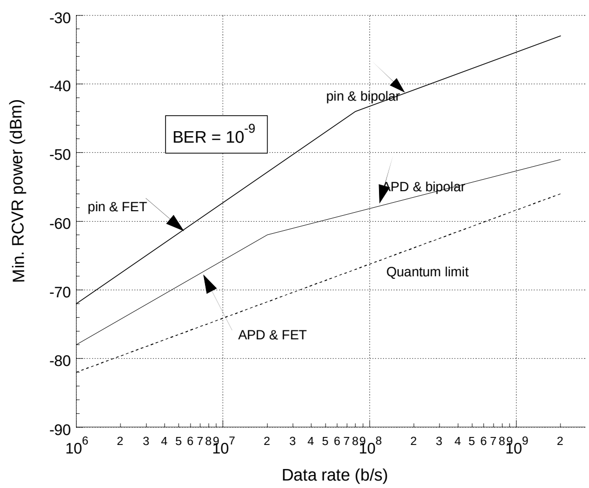
	Photodiodes			APDs	
	Si	Ge	InGaAs	Si	Ge
λ (nm)	400–1l00	500–1800	1000–1500	400–1100	500–1650
Quant. Eff	80%	50%	70%	80%	75%
t_{rise}(ns)	0.01	0.3	0.1	0.5	0.25
Bias (V)	15	6	10	170	40
$\Re_0$ (A/W)	0.5	0.7	0.4	0.7	0.6
M (gain)	1	1	1	80-150	80-150

- Silicon detectors
  - Mature technology
  - Operate close to theoretical limits in short-λ region
- InGaAs detectors
  - Useful in long-λ region
- Germanium-based detectors
  - Long-λ detector
  - Fundamental difficulties with
    - » Noise performance
    - » Noise in APDs and
    - » High dark current

Receivers: Summary (cont.)

- Noise contributions of preamplifier are important
  - High-impedance preamps
    - » Pros: best sensitivity
    - » Cons: need equalization amplifier
  - Transimpedance preamps
    - » Pros:
      - Simple design/operation
      - Increased dynamic range
    - » Con: increased noise
    - » Frequently-used receiver
- Representative sensitivities for BER of 10^{-9}

Fig. 6.23 p. 204



Receivers: Summary (cont.)

- **Observations...**
  - **Increased sensitivity required at higher B_R**
  - **Si FET receivers: good up to ~ 70 Mb·s^{-1}**
  - **GaAs MESFETs: higher B_R**
- **APDs**
  - **Pro: ~10 dB increased sensitivity**
  - **Cons:**
    - **More operating power required**
    - **Higher cost**
    - **Require temperature compensation**
- **Best detector/preamplifier combination**
  - **~10 dB from quantum-limited detection**